CSCanada
Advances in Petroleum Exploration and Development
Vol. 8, No. 1, 2014, pp. 37-42
DOI:10.3968/5674

ISSN 1925-542X [Print]
ISSN 1925-5438 [Online]
www.cscanada.net
www.cscanada.org

The New Method and Application of Friction Torque for Extended Reach Well

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Supported by National 863 Program "Key technology Development and Integration for Offshore Extended Reach Well Drilling And Completion" (No. 2012AA091501).

Received 23 August 2014; accepted 27 September 2014

Abstract

The extended reach well has the characteristics of long horizontal displacement, big hold angle and long open hole. The forecast and control of friction torque is one of the key factors of successful drilling of extended reach well. Based on the characteristics of extended reach well, considering the effect of drill string stiffness and drill string buckling on the friction & torque of the tube, a modified 3D soft-string calculation model for friction & torque of the extended reach well is proposed. The corresponding software has been programmed, and the model is applied in well A. The calculation result shows that the new method's calculation result is consistent with the experimental result, and the torque and hook load errors are within 10%. The method could satisfy the engineering requirement, which provide a good guidance for the friction & torque analysis in the process of profile optimal design and drilling operation for the extended reach well.

Key words: Extended reach well; Friction & torque; Drill string stiffness; Drill string buckling; Drilling operation

Jia, J. H., Yan, Z. L., Dou, Y. L., Huang, G. L., & Ma, Q. T. (2014). The new method and application of friction torque for extended reach well. *Advances in Petroleum Exploration and Development*, *8*(1), 37-42. Available from: URL: http://www.cscanada.net/index.php/aped/article/view/5674
DOI: http://dx.doi.org/10.3968/5674

INTRODUCTION

The extended reach well has the characteristics of long horizontal displacement, big hold angle and long open hole, so there are some technological difficulties such as the difficult trajectory control, serious pull press phenomenon, high demand of wellhore cleaning, difficult borehole stability and difficult casing running operation in the drilling process. The friction & torque are the main limit factor which influence the extend length. It is directly relevant to whether could reach the target. At present, the extensive research on friction torque model has been carried out. Because of the complexity of friction torque itself, the existing model prediction error is big, the torque error even could be more than 50%, and so how to make a perfect forecast on friction torque is the burning question for extended reach well research[1]. On the basis of the existing friction & torque calculation model, an advanced soft model is put forward, which is suitable for extended reach wells. The model can provide guidance for extended reach well design, drilling operation and well completion, and so forth.

1. MECHANICAL MODEL OF DRILLING STRING

The scholars have made extensive research on friction & torque and established some relevant mechanical models including soft model, hard model, bending beam model and finite element model[2]. The soft model does not consider the influence of string bending stiffness, the assumption of "string is completely coincide with borehole axis and it is continuous contact with the borehole" is unreasonable[3-4]. And it doesn't consider the influence of wellbore clearance, tube adapter, centralizer and other factors. Although considering the influence of tube string bending stiffness, the actual calculation result error is huge sometimes due to the high requirements for well track smoothness. When using bending beam model, it needs recalculate when the assumed contact point doesn't contact with the wall or a new contact point is appear. And if the number is big, it may lead to computational misconvenience[5]. The finite element model is so difficult that it is not suitable for on-site application. In addition, the contact problem and geometric large deformation double nonlinear problem is exist, the calculation time is very long and hard to convergence[6].

For extended reach well, borehole curvature is generally low. Under the condition of low borehole curvature, due to the friction & torque caused by drill string rigidity is relatively small, the soft model is used in the basic model of friction & torque calculation, at the same time, the drill string stiffness and buckling is considered to modify the model. The mechanical model is as follows.

1.1 Mechanical Model of a Unit of Drilling String

Soft model ignores the bending stiffness of drill string, and assumes that the axial line of the drill string is exactly the same as that of the borehole, and the drill string is a slender elastomer. So section analysis should be considered when the axial force and torque of drill string is analyzed. The force diagram of a unit of drill string is shown in Figure 1, the forces acting on a unit of drill string are buoyant weight W_b, the upper axial force T_1, the lower axial force T_2, Under the action of W_b, T_1 and T_2, the positive pressure N and frictional resistance F are produced between drill string and borehole, $F = N \times f$, f is Comprehensive coefficient of friction, including the friction between drill string and borehole wall and the borehole wall scraping from drill string shoulder, and so forth. In addition, some phenomena such as key seat, adsorption, hole shrinkage and cuttings bed can make a great resistance to drill string. These resistances are called abnormal friction, which are not taken into account in the model.

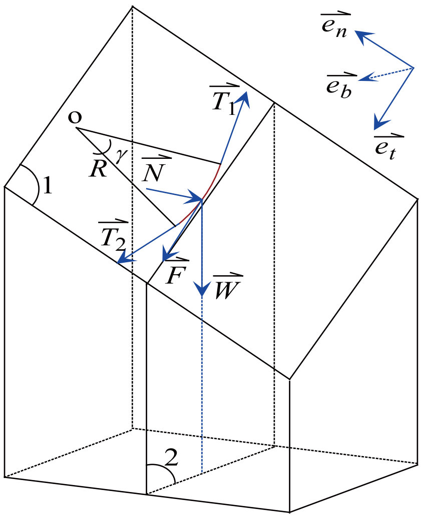

Figure 1
Mechanical Model of a Unit of Drilling String

1.2 Recurrence Formula for the Friction & Torque of the Drilling String

For calculating the friction & torque of the whole drilling string in borehole, the relations between different forces in a unit of the drilling string need to be analyzed at first. For a certain unit of the drill string, the known forces are the T_2 and W_b, and the solving forces are T_1, N, F and friction torque M. As the T_1 in this unit is just the T_2 in the lower unit, so the calculation could start from the bottom unit to the top unit and the whole friction & torque could be obtained by summing the F and M of each unit up. Obviously, at the beginning of the whole calculation process, the T_2 in the bottom need to be known. And the calculation formula of friction torque is as follows:

$a_1 = \sin\alpha_1 \cdot \sin\phi_1$ $\qquad$ $a_2 = \sin\alpha_2 \cdot \sin\phi_2$

$b_1 = \sin\alpha_1 \cdot \cos\phi_1$ $\qquad$ $b_2 = \sin\alpha_2 \cdot \cos\phi_2$

$c_1 = \cos\alpha_1$ $\qquad$ $c_2 = \cos\alpha_2$

$CX = (c_2-c_1)/[(a_2-a_1)^2+(b_2-b_1)^2+(c_2-c_1)^2]^{0.5}$

$CY = (c_2+c_1)/[(a_2+a_1)^2+(b_2+b_1)^2+(c_2+c_1)^2]^{0.5}$

$CZ = (a_1b_2-a_2b_1)/[(b_1c_2-b_2c_1)^2+(c_1a_2-c_2a_1)^2+(a_1b_2-a_2b_1)^2]^{0.5}$

$WX = W_b \times CX \quad WY = W_b \times CY \quad WZ = W_b \times CZ$

$$\begin{cases} N = \left\{ \left[(T_1 + T_2)\sin\dfrac{\gamma}{2} + WX \right]^2 + WZ^2 \right\}^{0.5} \\ F = N \cdot f_a \\ T_1 = T_2 + WY \pm F \\ M = 0.5 \cdot N \cdot f_c \cdot D \end{cases} \tag{1}$$

Where, α_1, α_2, ϕ_1, ϕ_2 are the inclination and azimuth of the up and down measure points for the string unit, rad; W_b is the buoyant weight of the string unit, N; T_1 and T_2 are the axial forces on the up and down cross sections of the string unit, N; γ is the dogleg angle of the certain unit, rad; N is the contact force between the string unit and the borehole wall, N; f is the comprehensive coefficient of friction resistance; F is the frictional resistance of the string unit, N; WX、WY、WZ are the component of the buoyant weight of the string unit on the principle, tangent and the binormal direction, respectively, N; a_1, a_2, b_1, b_2, c_1, c_2, CX, CY, CZ are all transition parameters. In equation (1), the symbol "+" is positive during pulling out of hole and "-" is negative on condition of running in hole.

The motion is mainly axial motion during tripping operation. So the torque and the friction torque of the drilling string are both zero and the axial force T_2 of the bottom unit equals to zero.

1.3 The Influence of the Rigidity on the Friction & Torque

The research shows that for the borehole with long or medium curvature radius, the average calculation error using the soft-string model or the hard-string model is less than 5%. Therefore, for the effect of the rigidity of the drilling string in borehole with small curvature radius (less than 150 m), Formula (2) could be suitable[7]. The additional positive normal pressure N_a could be applied for the modification of the soft-string model in order to reduce the calculation error for borehole with large curvature. And the formula used for calculation of N_a is shown as follows. The consideration of the rigidity here is totally different from the three dimensional hard-string model. Because for taking the rigidity into consideration, an additional positive normal force which is related with the curvature radius is added instead of the consideration of the rigidity deformation. This could both ensure the precision of the calculation and keep the quick calculating speed of the soft-string model.

$$\mathrm{Na} = 3.312\times10^{-3}EI/(R^3e)^{1/2} \tag{2}$$

Where

N_a - Additional positive normal force, N;

E - Elasticity modulus of drill string, the value could be 2.059×10^{11} Pa for hard material;

I - inertia moment of drill string, m^4; $I = (D^4\text{-}d^4)\pi/64$ (D is external diameter of the string, d is the inner diameter of the string);

R - curvature radius of the borehole, m;

e - clearance between the drilling string and the borehole, m.

1.4 The Influence of Buckling on the Friction Torque

The friction & torque calculation of the drilling string discussed above is conditionally-based on the hypothesis that the drilling string is not buckling. However, in most cases during the actual drilling process, the lower part of the drill string would be pressed and the buckling of the drilling string would take place when the axial comprehensive force of the pressed string surpasses the critical pressure[8-9]. As the buckling is an instable state of the drilling string when it is pressed, this would result in the rapid increase of the force between the string and the borehole wall and the consequent increase of the friction & torque.

Based on the difference of the buckling shape in the borehole, the buckling of the drilling string could be classified into two types: sinusoidal buckling and helix buckling[10-11]. Assuming that the corresponding critical force of the sinusoidal buckling and the helix buckling are F_{csin} and F_{chel} respectively, the calculation formula of the buckling critical load is as follows:

$$F_{\mathrm{csin}} = 2(EIw\times\sin a/e_0)^{1/2} \tag{3}$$

$$F_{\mathrm{chel}} = 2(2EIw\times\sin a/e_0)^{1/2} \tag{4}$$

Where

F_{csin} - Critical force of the sinusoidal buckling, N;

F_{chel} - Critical force of the helix buckling, N;

EI - Bending rigidity of the drilling string, $\mathrm{N\cdot m^2}$;

w - Weight of the string in the mud per length, N/m;

e_0 - Interval between the string joint and the borehole wall, m;

a_0 - Inclination of the well，rad. When a is less than p/60(3°), the value of a is p/60.

As the limitation of the borehole wall after the buckling of the drilling string, the stability of the string could be kept to a certain degree. But to a large extent, the buckling of the drilling string increases the contact force between the drilling string and the borehole wall which would make the friction and torque increase consequently. For the sinusoidal buckling, little error could be resulted in when the former friction model is applied. However, for the helix buckling, the former model should not be used for calculation. That's because an additional positive normal pressure would be added between the drill string and the borehole wall after the take place of the helix buckling. Based on the formula proposed by Mitchel in 1986, the formula used for the calculation of the additional positive normal pressure is as follows[12]:

$$N_s = e_0F^2/4EI \tag{5}$$

Where

N_s - Additional positive normal pressure on the drilling string per length, N/m;

F - Axial compressive force, N;

EI - Bending rigidity of the drilling string, $\mathrm{N\cdot m^2}$;

e_0 - Clearance between the string joint and the borehole wall, m;

Considering the buckling of the drill string, the positive normal pressure could be modified as follows:

$$N_i = N_i + e_0F^2/4EI \tag{6}$$

It can been seen from the formula above that the positive pressure is proportional to the square of axial pressure. The increase of the axial pressure would result in a bigger friction value and then the consequent increase of the axial pressure. In this vicious circle, the self-locking of the drill string would take place in the borehole wall.

2. CALCULATION EXAMPLE

Well A is a horizontal well used for unconventional development in shallow sea of Shengli oilfield which has the longest horizontal displacement. The TVD of this well is 3,341.9 m, horizontal departure is 3,185.14 m, the depth of the kickoff point is 1,200.9 m, and the biggest hole deviation angle is 92.7°.

2.1 Well Trajectory

The well trajectory of Well A is shown in Figure 2.

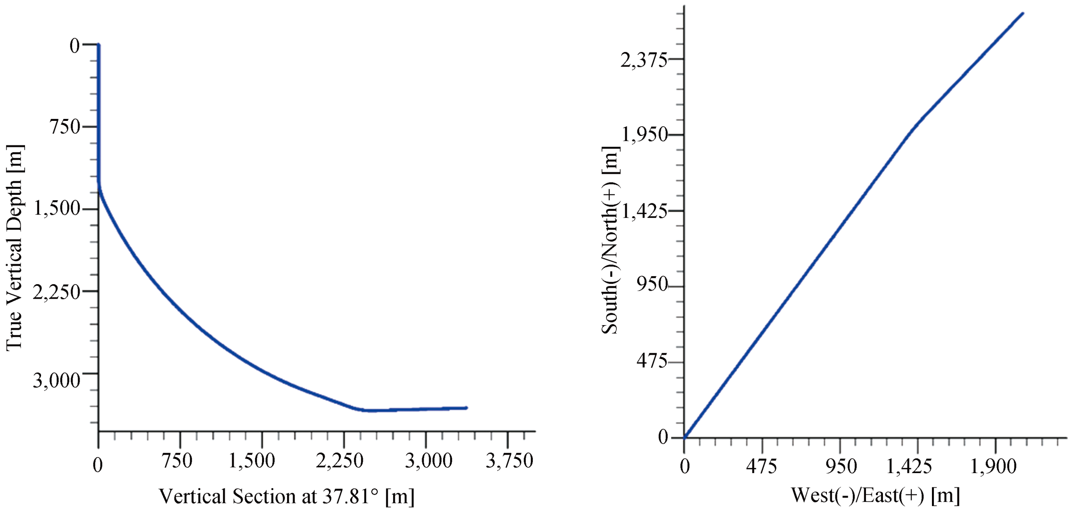

Figure 2
Projection Drawing of Well A Trajectory

2.2 Data of the Wellbore Configuration

Wellbore configuration of Well A is shown in Table 1.

Table 1
Wellbore Configuration of Well A

Parmater Spud	Well depth (m)	Bite size (mm)	Casing size (mm)	Casing setting depth (m)
First spud section	1,552	444.5	339.7	1,550
Second spud section	3,802	311.2	244.5	3,800
Third spud section	5,341	215.9	139.7	Liner casing (3,600 – 4,860) + sieve tube (4,860 – 5,341)

2.3 Related Parameters for Calculation of the Friction & Torque

Bottom-hole assembly: Φ215.9 mm PDC (Smith MD519) × 0.22 m + Φ172 mm 1.25° single-bend × 8.20 m + Φ205 mm Stabilizer × 0.75 m + (4A11×410) crossover coupling × 0.39 m + (411 × 410) Back pressure valve × 0.5 m + Sit key sub × 0.63 m + (411 × 520) × 0.37 + LWD × 5.9 m + (521 × 410) × 0.51 m + Φ127 mm non-magnetic bearing pressure drill pipe × 9.22 m + Current limiting nipple × 0.8 m + Φ127 mm drill pipe × 2,325 m + Φ127 mm heavy weight drill pipe × 227.08 m + Φ127 mm drill pipe (12 casing wear connectors).

Drilling parameter: Composite weight on bit 1 - 6 t, Directional weight on bit 1 - 8 t, displacement 28 - 29 L/s, pumping pressure 20 - 21 Mpa, rotating speed 70 rpm, 6 nozzle × 12 mm

Mud property: Density 1.40 g/cm^3, viscosity 70 s, plastic viscosity 25 mPa·s, yield value 13 Pa.

2.4 Result Analysis

The friction & torque of the third spud are calculated using the model above, and compared with the actual friction & torque value, and the results are listed in Table 2. As is shown in Table 2, compared with the actual measured value, the errors of the predicted friction & torque, hook load of tripping out or tripping in are all less than 10% and the calculated results of the predicted model could satisfy the engineering requirement.

Table 2
Accuracy of the Friction & Torque Prediction Results

Well depth m	Measured torque (kN·m)	Predicted torque (kN·m)	Error (%)	Measured hook load of tripping out (kN)	Predicted hook load of tripping out (kN)	Error (%)	Measured hook load of tripping in (kN)	Predicted hook load of tripping in (kN)	Error (%)
3,909	21	20.67	1.6	1,400	1,410.37	0.7	880	889.72	1.1
4,025	22	21.56	2	1,380	1,457.86	5.6	920	900.74	2.1
4,141	23	22.48	2.3	1,490	1,496.31	0.4	900	912.06	1.3
4,257	23	23.34	1.5	1,500	1,527.54	1.8	910	920.35	1.1
4,411	20	18.1	9.5	1,480	1,368.12	7.6	950	961.68	1.2
4,576	19	19.67	3.5	1,410	1,390.75	1.4	950	957.56	0.8
4,692	22.5	20.81	7.5	1,450	1,397.17	3.6	920	954.06	3.7
4,808	22	21.55	2	1,420	1,391.97	2	920	947.39	3
5,021	24	22.57	6	1,373	1,414.86	3	980	922.35	5.9
5,245	24	23.81	0.8	1,380	1,424.37	3.2	900	917.79	2
5,341	22.5	24.26	7.8	1,380	1,426.06	3.3	920	913.06	0.8

COUCLUSION

(a) Based on the comprehensive analysis of the existing model for calculating the friction & torque, a modified calculation model for friction & torque of the extended reach well is proposed. This model is a new model for calculating the friction & torque in oil field which has the characteristics of easy calculation process and reliable calculation results and takes all effects of drill stiffness, drill string buckling on the friction & torque of the tube into consideration. The model is applied in well A and the calculation result shows that it could satisfy the engineering requirement which lay a good foundation for application of the profile optimal design of the extended reach well and the friction & torque calculation model.

(b) The value of the friction & torque is affected by lots of factors and these effects are hard to be accurately reflected by mathematical model. So, when predicting the friction & torque, it would be better to back calculate the related coefficient of friction resistance at first using the actual friction & torque data for the same borehole and the same working condition. Then, the friction & torque could be predicted using the calculated coefficient of friction resistance.

(c) The friction & torque should be reduced to the greatest extent during the construction process of the extended reach well. And this could be realized by optimizing well path, improving drilling fluid lubricity (such as using oil base drilling fluids and improving the oil-water ratio), using vibration anti-friction tool, removing cuttings in the well in time and so forth.

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